

“Chain” Galaxies are Edge-On Low Surface Brightness Galaxies

Julianne J. Dalcanton^{1,2} & Stephen A. Sackett

Observatories of the Carnegie Institute of Washington

813 Santa Barbara Street, Pasadena CA, 91101

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¹e-mail address: jd@ociw.edu

²Hubble Fellow

ABSTRACT

Deep *HST* WFPC2 images have revealed a population of very narrow blue galaxies which Cowie et al. (1996) have interpreted as being a new morphological class of intrinsically *linear* star forming galaxies at $z = 0.5 - 3$. We show that the same population exists in large numbers at low redshifts ($z \approx 0.03$) and are actually the edge-on manifestation of low surface brightness disk galaxies.

Subject headings: galaxies:evolution, galaxies:general, galaxies:irregular,
galaxies:structure

1. Introduction

The launching of the Hubble Space Telescope has for the first time allowed astronomers to observe the morphology of galaxies at moderate redshifts. Coupled with deep redshift surveys, *HST* imaging provides a powerful tool for studying the evolution of galaxies, in particular, the ubiquitous but poorly understood population of “excess” faint blue galaxies. A recent paper by Cowie et al. (1996; hereafter CHS) reports that many of the blue galaxies in deep F814W *HST* images of two fields from the Hawaii Redshift Survey appear to be very narrow, linear structures. The galaxies tend to be very straight, and have sizes between 2-3'' in the long dimension and are marginally resolved after deconvolution at 0.05-0.1'' in the narrow dimension. CHS argue that the extreme ellipticity of these galaxies and the lack of continuity between the linear “chain” galaxies with the rest of the galaxy population is incompatible with their being edge-on disk galaxies. They therefore treat these galaxies as a distinct morphological class of *intrinsically* linear galaxies which they refer to as “chain” galaxies. Two of the chain galaxies are emission line galaxies at redshifts of $z \approx 0.5$, another is argued to be at $z \approx 1.4$ based upon one strong emission line, and a fourth is suggested to be at $z = 2.4$ based on interpreting a break in the continuum at 4000Å as the onset of intergalactic Ly- α forest absorption. On the basis of the emission lines and blue colors, coupled with the short lifetime expected for intrinsically linear structures, CHS argue that their new morphological class of chain galaxies are not only star-forming, but are in the process of formation (see also Ogorodnikov 1967).

The conclusions of CHS that chain galaxies represent a new morphological class of linear galaxies in the process of forming at $z = 0.5 - 3$ is based on the following observations: 1) the extreme ellipticities 2) the lack of continuity between the chain galaxies and the rest of the galaxy population and 3) the lack of any low redshift counterparts. In this paper we will first show that the extreme ellipticities are not incompatible with chain galaxies

being intrinsically disk systems viewed edge-on. We will then use data from an ongoing ground-based redshift survey of low surface brightness galaxies to show that there are large numbers of galaxies with similar morphology at very low redshifts ($z \approx 0.03$) and that they join seamlessly onto the population of edge-on normal galaxies. Furthermore, we will show that the low redshift galaxies with the “chain” morphology are consistent with their being the edge-on manifestation of face-on low surface brightness galaxies (LSBs) found in the same survey.

2. Extreme Ellipticities & Morphology

It is on the basis of their very large axial ratios that CHS argue that the chain galaxies cannot be intrinsically disk systems. The 21 chain galaxies observed in the CHS images have a mean axial ratio of 4.7 ± 2.3 at the 20% of peak isophotal level in the undeconvolved surface brightness profile, with a maximum observed axial ratio of 9.5. When the images are deconvolved with the point spread function (FWHM = $0.19'' - 0.22''$), CHS find transverse widths of $0.05 - 0.23''$, which are 0.25 – 1.15 times the full width at half maximum of the HST point spread function. Assuming that the observed axis length is the quadrature sum of the intrinsic axis length and the width of the point spread function at half maximum, we can calculate the distribution of intrinsic axis ratios from the undeconvolved axial ratios published by CHS. These are plotted in Figure 1 as a function of their observed axial ratios, with the symbols coding the deconvolved transverse widths of the galaxies. While the bulk of the chain galaxies have deconvolved axial ratios of between 2 and 14, there are some galaxies with deconvolved axial ratios extending up to 33. Note, however, that all of the very large axial ratios are associated with extremely small deconvolved minor axis lengths; all of the galaxies with $a/b > 20$ have deconvolved minor axis lengths which are significantly smaller than a single WFPC2 pixel. Therefore, the largest axial ratios are by far the most

uncertain.

We wish to show that such extreme axial ratios are not necessarily inconsistent with disk galaxies viewed edge-on. Rather than invoking theoretical models, we can resort to observations of extremely thin edge-on galaxies at low redshift to demonstrate that galaxies with the “chain” morphology do not necessarily require a new morphological class.

In the past twenty-five years there has been a sporadic commentary on the existence of very elongated edge-on galaxies. Vorontsov-Velyaminov (1967) and de Vaucouleurs (1974) both give examples of galaxies with axial ratios which are larger than 10:1. The published photographs of these flat galaxies all show the knotty structure that CHS identify with the “chain” galaxies. Most illuminating are the additional examples from Vorontsov-Velyaminov (1967) which have both a extremely flat, low surface brightness disk ($a/b > 20$) and a prominent bulge; this provides uncontrovertible evidence that there are true disks at low redshift with the extreme axial ratios observed by CHS. Furthermore, a dynamical study of extremely thin galaxies by Goad & Roberts (1981) show that the galaxies are rotating around their minor axis, as would be expected if they were simply edge-on disks.

More recently, Karachentzev et al. (1993) have compiled a catalog of edge-on galaxies (the Flat Galaxy Catalog) which have $a > 40''$ and $a/b \geq 7$ on the Palomar Observatory Sky Survey and ESO/SERC survey plates. An analysis of the catalog by Kudrya et al. (1994) shows that there are extremely flat low-redshift galaxies which have $a/b \approx 22$, flatter than 80% of the CHS chain galaxies. Furthermore, using the distribution of observed axial ratios to determine the maximum disk flattening (i.e. to correct for inclination effects), they find that the galaxies become progressively thinner with later Hubble types, with the limiting axial ratio varying from $a/b_{max} = 14.1$ for Sb galaxies to $a/b_{max} = 27.0$ for Sd’s. Thus, there are edge-on disks which are as thin as the galaxies in the CHS data, particularly among the later Hubble types.

3. “Chain” Galaxies at Low Redshift

The steady increase in disk ellipticity with increasing Hubble type observed in the Flat Galaxy Catalog is also accompanied both by a decrease in the mean surface brightness and by an increase in the fraction of galaxies with pronounced asymmetry (from 17% for Sb galaxies to 83% for Sdm galaxies) (Karachentzev et al. 1993, Guthrie 1992). These trends are also manifested in the high-redshift chain galaxies, where the thinnest galaxies are also marked by lumpy morphologies embedded in an extended, linear low surface brightness component.

It is not unreasonable to assume that the increase in axial ratios, decrease in surface brightness, and increase in asymmetry would continue ever further along the Hubble sequence into the low surface brightness Sm/Im classes. There are many examples of Im and Sm galaxies which, when viewed face on, appear to be disks with only one or two HII regions superimposed. If such galaxies were viewed edge on, and particularly if they continue the trend for late-type galaxies to have progressively thinner disks, then they would likely be observed to have the chain morphology. Most importantly, Marzke et al. (1994) have shown that Sm/Im galaxies begin to dominate the luminosity function fainter than $M^* - 1$, and thus the high surface density of galaxies with the chain morphology at intermediate redshifts may not be surprising, if the galaxies are primarily more than one magnitude fainter than M^* . The three chain galaxies in CHS with well determined redshifts do have absolute K magnitudes between 1 and 4 magnitudes fainter than the value of M^* reported by Mobasher et al. (1993); however, more redshifts are needed before any conclusions about the expected surface density can be made.

Based on the above trends, we believe that edge-on Sm and Im galaxies are the true counterparts to the chain galaxies observed at intermediate redshift. To establish this link, however, we must first identify low redshift galaxies which also share the chain

morphology, and then we must show the continuity between this population and the rest of the Sm/Im galaxy population. The most notable feature of the Sm and Im classes is their very low surface brightness (with the exception of the fraction of actively starbursting galaxies such as NGC4449) and as such, the bulgeless low surface brightness galaxies (LSBs) being found in recent surveys (Impey, Bothun, & Malin 1988, Bothun, Impey, & Malin 1991, Schombert et al. 1992, Schombert & Bothun 1988, Irwin, Davies, Disney, & Phillipps 1990, Turner, Phillipps, Davies, & Disney 1993, de Jong 1995, Dalcanton 1995 and references therein) are best viewed as extreme members of this Hubble type (Dalcanton et al. 1996). Morphologically, many of the LSB images published by Schombert et al. (1992) are indistinguishable from Im galaxies observed in Virgo (Sandage & Binggeli 1984), although the Schombert et al. (1992) galaxies tend to have larger physical sizes. Thus, samples of nearby LSB galaxies are likely places to find low redshift galaxies with the chain morphology observed at intermediate redshifts.

Further support for the LSB-chain galaxy connection comes from a dynamical study of low redshift “superthin” galaxies by Goad & Roberts (1981). After measuring rotation curves for four galaxies with axial ratios up to 20:1, as well as for two comparison galaxies, Goad & Roberts found that the “superthin” galaxies have very shallow velocity gradients in their centers. The slow rise towards the halo-dominated, flat portion of the rotation curve suggests that the disk of the superthin galaxies contributes very little mass to the inner parts of the galaxies. As discussed in Dalcanton et al. (1996), this is a general property expected for the low surface density disks of LSBs.

3.1. The Las Campanas Redshift Survey of LSBs

We have recently completed an extension to the Las Campanas Redshift Survey (LCRS; Shectman et al. 1992) which is designed to measure the contribution of galaxies

with intrinsically low surface brightness to the local galaxy luminosity function. The new survey, the Low Surface Brightness Extension (LSBX), used 14.5 square degrees of the original r band survey data from the LCRS to identify a sample of 672 galaxies with faint aperture magnitudes (up to 1.5 magnitudes fainter than the aperture magnitudes in the LCRS) but large angular scale lengths; this procedure aims to identify intrinsically low surface brightness galaxies within a volume comparable to the volume probed by the LCRS, in spite of the fainter magnitude limit. The observed galaxies were chosen randomly from among all galaxies satisfying the selection criteria. The multi-fiber spectrograph on the Dupont 2.5m at Las Campanas (Schechter 1993) was used with a resolution of 5\AA to measure redshifts to the target galaxies in three different fields, with an average exposure of 8 hours per field. After sky subtraction, cross-correlation with A and F star templates, and identification of emission lines, we successfully measured redshifts for 91% of the galaxies in the sample; the median redshift of the sample is $z = 0.11$, and 90% of the galaxies lie at redshifts less than 0.25. The details of the data acquisition and reduction will be discussed in Dalcanton & Schechter (1996).

Because the resulting sample, when combined with the original LCRS, spans a range of central surface brightness of over a factor of 40, it provides a nearly ideal sample for 1) identifying galaxies with the chain morphology at low redshifts and 2) demonstrating the continuity of the chain morphology with normal galaxies. For the purposes of this paper, we will be working with a volume limited subsample, consisting of the 75 galaxies in our sample with recessional velocities between 10,500 km/s and 15,500 km/s ($z_{\text{median}} = 0.038$, and 90% of the galaxies are within 1000 km/s of the median velocity); the velocity range was chosen to fully encompass a significant “wall” in the galaxy distribution. The subsample contains galaxies with isophotal r -band magnitudes between 14.5 and 19.

3.2. Continuity With Edge-On Normal Galaxies

To show that there are low-redshift galaxies with the chain morphology and that they form a continuum with high-surface brightness edge-on normal galaxies, we selected galaxies from the volume limited subsample which have ellipticities ($\epsilon \equiv 1 - b/a$) greater than 0.6. Figure 2 shows the eight galaxies, the five faintest of which are from the low surface brightness extension, arranged in order of decreasing mean surface brightness. First, note that within the limits of the ground based resolution, the low surface brightness galaxies are close morphological analogs of the chain galaxies observed at moderate redshift in HST imaging. For example, the five lowest surface brightness galaxies in Figure 2 are remarkably similar to CHS’s “chain” galaxies number 23, 14, 3, 9, and 4, including hints of the knots seen in the deeper, high-resolution HST imaging. Second, note that there is a natural progression from edge-on normal galaxies, which have both a recognizable bulge component and a high surface brightness disk, through galaxies which have a high surface brightness disk but no visible bulge and finally to highly elongated galaxies with very low disk surface brightnesses. This suggests that the extreme thin, low surface brightness galaxies at the end of this sequence exist in continuity with the population of normal disk galaxies viewed edge on.

To put this impression on a more quantitative footing, the axial ratios were measured at the isophote corresponding to 20% of the peak surface brightness, following the method used by CHS, and are plotted in Figure 3 as a function of their central surface brightness³. All but three of the twenty-one “chain” galaxies identified by CHS have unconvolved axial ratios smaller than the largest axial ratio in our small sample, and the axial ratios of the

³after including an optically-thin correction to the observed peak surface brightness – $\Delta\mu_0 = 2.5 \lg(\frac{a/b}{N})$, where N is the number of exponential scale lengths corresponding to $a/2$. $N = 2.4$ for a measured at the 20% of peak isophotal surface brightness

remaining three are only 20% larger. Thus, in the unconvolved data, there is very little difference in the range of ellipticities of our sample and the CHS sample. Two of the eight galaxies in our sample are unresolved in the minor axis, and thus their measured axial ratios are lower limits to their true axial ratios. Furthermore, the percentage of unresolved galaxies (25%) is the same as in the CHS data (Figure 1). Therefore, the very thin structures being uncovered in deep HST imaging have structural analogs at low redshift, and are therefore not necessarily a manifestation of a unique state of galaxy formation at moderate to high redshifts.

3.3. Continuity With Face-On LSBs

To show that the thin faint galaxies in Figure 2 are actually disks, we must not only show their continuity with the disks of normal galaxies; we must find their face-on low surface brightness counterparts and show that the population as a whole is consistent with thin disks seen from random viewing angles. We show in Figure 4 all galaxies in the volume limited subsample with a central r -band surface brightness fainter than 21.3 (roughly 0.5 magnitudes below the Freeman (1970) value, assuming $\langle B - r \rangle \sim 0.8$ (de Blok et al. 1995)), and in Figure 5, we show their cumulative distribution of ellipticities (again measured as in CHS). The lightly shaded region corresponds to the range of ellipticities which with a galaxy having the median major axis length would be unresolved in the minor axis, and the heavily shaded region marks the range of ellipticities which with a galaxy whose major axis length was in the top 95% would be unresolved in the minor axis. The measured ellipticities of galaxies falling within this region are therefore likely to underestimate the true ellipticities, and thus very little interpretation can come from the detailed distribution of ellipticities in this regime, beyond noting that the distribution is continuous. This again suggests that galaxies at low redshift with the “chain” morphology

are *not* a disjoint population; they form a continuous distribution with face-on LSB galaxies, in addition to being morphologically continuous with edge-on normal galaxies. In fact, the distribution of ellipticities outside of the heavily shaded region is indistinguishable from what would be expected for a single population of perfectly thin, circular disk galaxies viewed at random inclinations (the straight diagonal line in Figure 5, which has only a 50% chance of not being representative of the distribution of ellipticities, by the Kolmogorov-Smirnov test). Clearly, there is nothing to suggest that the very thin galaxies in Figures 2 & 4, as well as in deep HST images, are anything more than low surface brightness *disk* galaxies viewed edge on.

Although the edge-on circular disk model provides a statistically adequate fit to the distribution of ellipticities, there are indications of a possible paucity of face-on galaxies. This may reflect an intrinsic non-circularity of LSB disks. We note in passing that a better fit to the ellipticity distribution results from adding the assumption that the disks are not perfectly circular, and have an intrinsic ellipticity of $\epsilon_0 = 0.27$ (the curved line in Figure 5, calculated from Monte Carlo simulations of the observed ellipticity of intrinsically noncircular disks; see Rix & Zaritsky 1995). Note that few, if any, of the galaxies in Figure 4 appear to be circularly symmetric galaxies viewed from an angle; this is not surprising, given that vast majority of chain galaxies in CHS are likewise asymmetric.

4. Colors, Magnitudes, and Surface Brightnesses

Low redshift LSBs are among the bluest galaxies known (McGaugh & Bothun 1994, de Blok et al. 1995, Knezek 1993, de Jong 1995). Similar claims are made for the chain galaxies published by CHS. Although the almost total lack of redshifts for the chain galaxies makes a direct comparison between chain and LSB colors somewhat difficult, with some reasonable assumptions we can estimate appropriate *k*-corrections for the chain galaxies.

We first assume that the blue colors suggest that the CHS galaxies have spectral energy distributions characteristic of irregular galaxies. Secondly we assume that the bulk of the chain galaxies lie between $z = 0.5$ and $z = 1.5$, which encompasses the range spanned by the three securely measured redshifts in the chain galaxy sample. Adopting the k -corrections for Im galaxies published in Cowie et al. (1994), the $B - K$ and $B - I$ k -corrections are therefore in the ranges $1.2 - 1.4$ and $-0.1 - 0.4$, respectively. The median $B - K$ color for the CHS chain galaxies is 4.1, and their median $B - I$ color is 1.5; these correct to $\langle B - K \rangle \approx 2.8$ and $1.1 \lesssim \langle B - I \rangle \lesssim 1.6$ at zero redshift.

We can compare the k -corrected chain galaxy colors to the published $B - I$ colors of LSBs studied by de Blok et al. (1995) and by McGaugh & Bothun (1994), and to the $B - K$ colors of the face-on disk galaxies studied by de Jong (1996). The two former were drawn from the Schombert et al. (1992) catalog and the Uppsala General Catalog (UGC; Nilson 1973), and the latter were drawn entirely from the UGC. The LSBs in the de Blok and the McGaugh & Bothun catalogs catalog have $1 < B - I < 1.3$ and $1.1 < B - I < 2.3$ respectively, and the late type ($T > 6$) galaxies from de Jong (1996) have $B - K \approx 2.8$. Therefore, the range of colors spanned by the published LSB samples is completely consistent with the blue colors of the CHS chain galaxy samples

We wish to make the additional point that the properties of the CHS chain galaxies are included in the range of surface brightness and absolute magnitude spanned by the low redshift galaxies in Figure 2. The three CHS chain galaxies with secure redshifts have k -corrected absolute B magnitudes between 2.1 magnitudes below M_* and 1 magnitude above M_* (using M_* as calculated by Efstathiou et al. 1988), while the low redshift galaxies in Figure 2 have absolute r magnitudes between 3.1 and 0.3 magnitudes below M_* (using M_* from Lin et al. 1996). The linear sizes of the galaxies in both samples suggest exponential disk scale lengths of $1 - 4 h_{75}^{-1}$ kpc (given that the major axis lengths were measured at 20%

of the peak surface brightness of an edge-on disk). The combination of similar absolute magnitudes and similar scale lengths immediately suggest that the LSBs in Figure 2 and the CHS chain galaxies have comparable surface brightnesses. This conclusion also holds if one compares the mean surface brightnesses for each individual galaxy in the two samples, assuming $B - r \approx 0.8$ (de Blok et al. 1995).

5. Conclusions

We have shown that the apparently unfamiliar population of very thin galaxies revealed in deep HST imaging do in fact have low redshift counterparts among the population of low surface brightness disk galaxies, and thus, that there is no immediate need to invoke any evolutionary scenario to explain their appearance at moderate redshifts. We have shown examples of such very thin galaxies in existing catalogs of nearby galaxies, and shown the statistics of the ellipticity distributions of low-redshift LSB galaxies are consistent with the low redshift “chain” galaxies being edge-on manifestations of disks. This suggests that, at low redshift, such thin systems are *not* necessarily intrinsically linear (as opposed to disk), bringing into question the assumption that equally thin systems at high redshift *cannot* be disks (CHS). Our conclusion that the thin “chain” galaxies observed at moderate to high redshifts are analogs of low surface brightness disks is supported by both their morphologies and by their colors as well. LSBs at low redshift are intrinsically asymmetric (Figure 5), often with one or two bright knots superimposed upon a diffuse low surface brightness disk (Figure 4); such systems, when viewed edge-on, would be consistent with the lumpy structure of some of the chain galaxies. The moderate redshift chain galaxy / low redshift edge-on LSB class may be viewed simply as a subset of the link between the faint blue galaxies and nearby LSBs posited by Ferguson & McGaugh (1995).

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Fig. 1.— Deconvolved axial ratios as a function of measured axial ratio for the 21 Cowie et al. (1996) chain galaxies. The deconvolved axis ratios are estimated using $b_{observed}^2 = b_{intrinsic}^2 + \sigma^2$, where σ is the width of the point spread function at half maximum and b is the minor axis length, and assuming that $a_{observed} \approx a_{intrinsic}$. Galaxies whose deconvolved minor axis lengths are less than $\sigma/3$ are marked with solid circles, between $\sigma/3$ and $2\sigma/3$ are marked with open triangles, and all others are marked with crosses.

Fig. 2.— Edge-on galaxies ($\epsilon > 0.6$) from the volume limited $z \approx 0.04$ LCRS+LSBX subsample, arranged in order of decreasing central surface brightness. Their distribution of axial ratios as a function of central surface brightness is plotted in Figure 3.

Fig. 3.— Axial ratio vs central surface brightness for flattened galaxies in the volume limited $z \approx 0.04$ LCRS+LCRX subsample (Figure 2). The ellipticity is measured at 20% of the peak surface brightness, analagous to CHS. Galaxies whose minor axis length are less than 33% larger than the seeing are marked with solid circles, between 33% and 66% are marked with triangles, and all others are marked with crosses. Note that the range of observed axial ratios is almost identical to those observed in the deep HST imaging (Figure 1), although the galaxies are at much lower redshift.

Fig. 4.— A volume limited sample of low surface brightness galaxies ($\mu_0 > 21.3 r \text{ mag/arcsec}^2$) from the volume limited $z \approx 0.04$ LCRS+LSBX subsample. Note that some of the galaxies have one or two assymmetrically placed knots embedded within a lower surface brightness halo; presumably, these systems would look very similar to the knottier of the chain galaxies, if they were to be viewed edge on at high resolution. Their distribution of ellipticities is plotted in Figure 5.

Fig. 5.— Cumulative distribution of ellipticities of the LSB subsample from Figure 4 (heavy stepped line), compared to the predicted cumulative distribution of ellipticities for

perfectly flat circular disks (diagonal light line) and perfectly flat elliptical disks with intrinsic ellipticity $\epsilon_0 = 0.27$ (curved light line). The median uncertainty in measured ellipticities is ± 0.1 . To show how seeing limits the maximum observed ellipticity, the light hashed region is where a galaxy with the median major axis length would have a minor axis length that was less than 25% larger than the seeing width, and the dark shaded region is where a galaxy whose major axis was larger than 95% of the galaxies in the subsample would have a minor axis length that was less than 25% larger than the seeing width; in these regions, the distribution of ellipticities is expected to deviate from random.

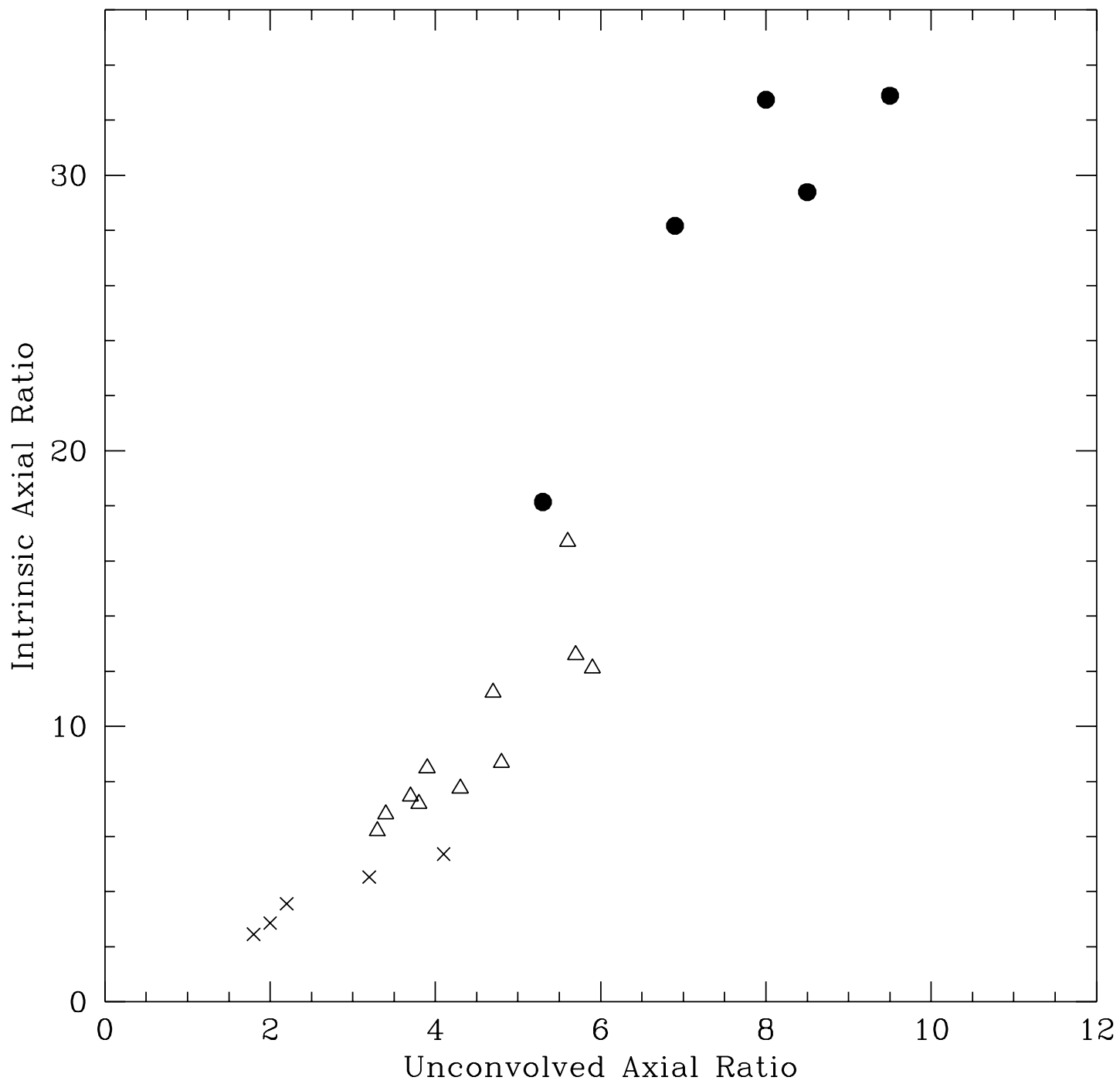


FIGURE 1

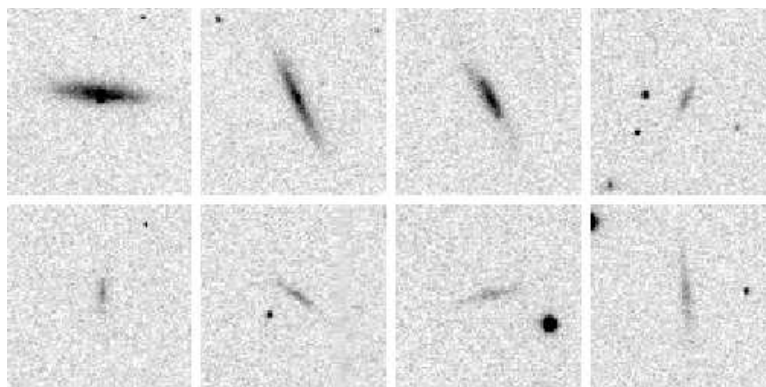


FIGURE 2

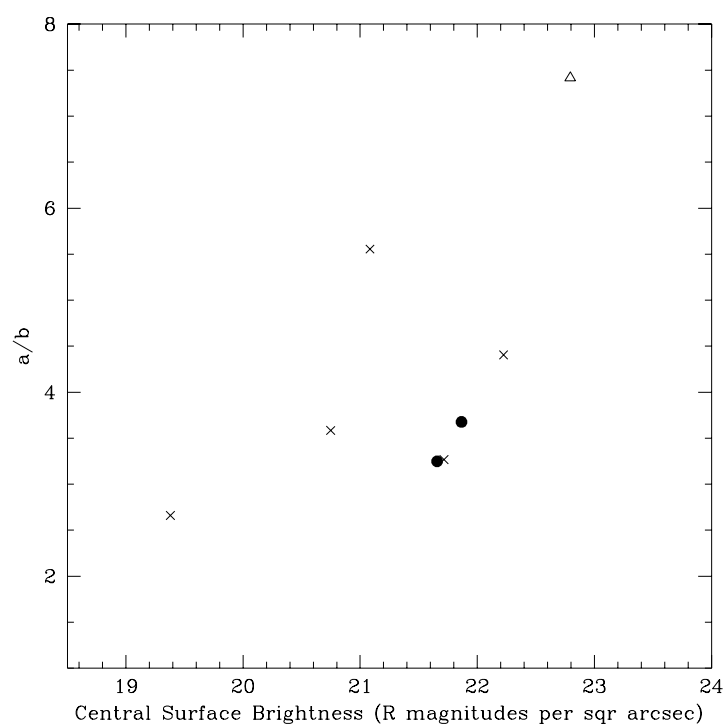


FIGURE 3

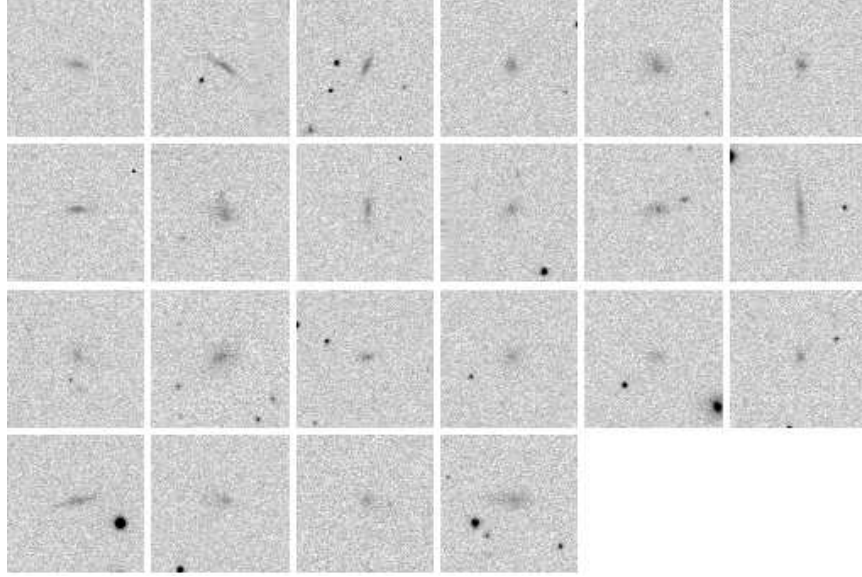


FIGURE 4

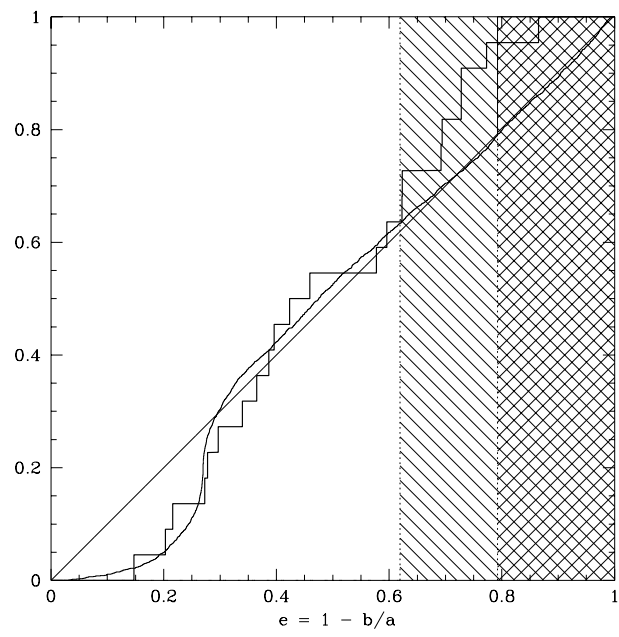


FIGURE 5